An Operational Real-Time Eddy-Resolving 1/16° Global Ocean Nowcast/Forecast System

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Abstract*-A real-time eddy-resolving global ocean nowcast/forecast system has been running at the Naval Oceanographic Office (NAVOCEANO) since 18 October 2000 and it became an operational product on 27 September 2001. The system, which was developed at the Naval Research Laboratory (NRL), uses the NRL Layered Ocean Model (NLOM) with 1/16° resolution and seven layers in the vertical. Real-time satellite altimeter sea surface height (SSH) from Topex/Poseidon, ERS-2 and Geosat-Follow-On provided by NAVOCEANO's Altimeter Data Fusion Center, are assimilated into the model. The large size of the model grid (4096x2304x7) and operational requirements makes it necessary to use a computationally efficient ocean model and assimilation scheme. The assimilation consists of an optimum interpolation (OI) deviation analysis of SSH with the model as a first guess, a statistical inference technique for vertical mass field updates, geostrophic balance for the velocity updates outside of the equatorial region and an incremental updating of the model fields to further reduce gravity wave generation. A spatially varying mesoscale covariance function determined from Topex/Poseidon and ERS-2 data is used in the OI analysis. The sea surface temperature (SST) assimilation consists of relaxing the NLOM SST to the Modular Ocean Data Assimilation System (MODAS) SST analysis which is performed daily at NAVOCEANO. Real-time and archived results from the model can be viewed at the NRL web site http://www.ocean.nrlssc.navy.mil/global_nlom. This includes many zoom regions, nowcasts and forecasts of SSH, upper ocean currents and SST, forecast verification statistics, subsurface temperature cross-sections, the amount of altimeter data used for each nowcast from each satellite and nowcast comparisons with unassimilated data. The results show that the model has predictive skill of the mesoscale variability for at least one month.

I. INTRODUCTION

In the last few years, several important elements have reached a status where it is possible to perform eddy-resolving global ocean prediction. These elements include, computing power, real-time data input, numerical ocean models and data assimilation capabilities. In this paper, we describe the first near global eddy-resolving ocean prediction system. It has been running continuously at the Naval Oceanographic Office (NAVOCEANO) since 18 October 2000 and became an operational product 27 September 2001. This is a first generation nowcast/forecast system. It will be upgraded and improved as new ocean models and assimilation techniques become available.

In section II, the system with its different components is described. Results from the operational system are discussed in section III. The value of having an eddy-resolving global prediction system and future upgrades to the current system are discussed in section IV. A more detailed description of the nowcast/forecast system can be found in [1].

II. THE NOWCAST/FORECAST SYSTEM

A. The NRL Layered Ocean Model (NLOM)

The model component of the ocean prediction system is the NLOM. It is based on the primitive equation model of [2] but with greatly expanded capability [3, 4, 5, 6]. The model has a nearly global domain that extends from 72°S to 65°N. The horizontal resolution of each model variable is 1/16° in latitude by 45/512° in longitude, which is eddy-resolving. The model has lateral boundaries that follow the 200 m isobath. It has 6 dynamical layers plus the mixed layer and realistic bottom topography that is confined to the lowest layer of the model. At the solid boundaries kinematic and no-slip boundary conditions are used. Fig. 1 shows the sea surface temperature (SST) for 22 July 2002 over the near global domain.

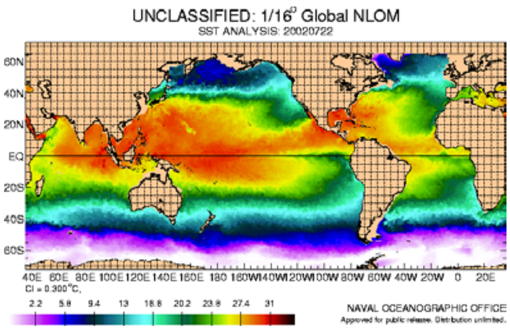


Fig. 1. The 1/16° eddy-resolving NLOM SST (°C) for 22 July 2002.

The prognostic variables in the model are layer density, layer thickness, and layer volume transport (layer velocity times layer thickness). The model has a free surface, corresponding to sea surface height (SSH) (a variable observed by satellite altimetry). The embedded mixed layer model carries prognostic equations for the SST and the mixed layer depth (MLD). The mixed layer is not confined to be within the upper dynamical layer (i.e., floating mixed layer). It is to some extent independent of the dynamical layers; however, it is not entirely passive.

B. The assimilation scheme

In an operational setting, it is important to have an efficient model and assimilation scheme. A limited amount of computer time will be available for the daily model run. Due to the large size of the 1/16° NLOM, we are restricted to use a relatively simple assimilation technique. The mathematically more sophisticated techniques may increase the model run time by a factor of 100, (e.g., ensemble Kalman filter [7]) compared to the model run without assimilation. The current assimilation system increases the run time by about 1½.

The assimilation scheme is similar to the incremental updating technique described in [8]. It includes an OI deviation analysis using the model SSH as the first guess. The correlation length scales determined by [9] are used in the deviation analysis. The surface information from the satellite data are transferred to the lower layers of the model using a statistical inference technique [10]. The pressure fields in all layers are updated by this method. The velocity fields in all layers are updated using a geostrophic correction calculated from the pressure changes. The velocity correction is not performed within 5° latitude of the equator. Between 5-8° the correction is gradually increased to full strength using a hyperbolic tangent function. The model variables are then incrementally updated to minimize the creation of inertia-gravity waves.

The SST assimilation consists of a relaxation toward the Modular Ocean Data Assimilation System (MODAS) MCSST, [11], analyses with a 3-hour e-folding time scale. During the forecast period, it is relaxed toward climatologically corrected persistence of the nowcast SST with a relaxation time scale of 1/4 the forecast length (i.e., 1 day for a 4-day forecast and 1 week for a 4-week forecast). This is a necessary step for the long-term (e.g., 30-day) SST forecasts because the forecast atmospheric thermal forcing is only available out to five days, and unlike the evolution of the mesoscale variability it responds rapidly to atmospheric forcing. The model value added during the forecast is to keep SST+SSH fronts aligned and to make the SST much more fluidic. No such relaxation is performed for SSH since the evolution of most circulation features is more sensitive to internal dynamics than atmospheric forcing on a 30-day timescale.

C. The mean sea surface height

Unfortunately, the geoid is not known accurately enough on scales important for the resolution of the mesoscale. Thus, the satellite altimeter data consists of SSH anomalies with respect to the mean over the period that the satellite has been flying. In order to assimilate these anomalies a mean SSH must be used. Our approach is to use a model mean over the period of the satellite data. It is crucial that the mean SSH has the correct position of the major current systems. The fronts should also be more sharply defined than what is feasible from hydrographic climatologies. In order to obtain this a fully eddy-resolving model is necessary. Other sources of information are used to compare the model mean. This includes the mean dynamic height calculated from available temperature and salinity measurements modified by data taken over the time-period of the satellite data. The mean frontal positions determined from satellite IR and the variability from satellite altimeter data is also used to determine the position of fronts. A rubber-sheeting technique is used to modify the model mean as needed to better match the independent observations. The rubber-sheeting application suite is a collection of computer programs specifically designed to operate on SSH fields.

It includes methods to move masses of water in an elastic way (hence rubber-sheeting), merge data, overlay contours from a second reference field and raise or lower the values of a region

D. The wind and thermal forcing

The thermal and wind stress forcing come from the Fleet Numerical Meteorology and Oceanography Center (FNMOC) Navy Operational Global Atmospheric Prediction System (NOGAPS) [12]. A hybrid approach is used for the wind stress. The long term mean (August 1990 - July 1999 for FNMOC) is subtracted from the FNMOC stresses and replaced with the [13] (HR) annual mean. The hybrid approach has been used successfully with the HR and European Centre for Medium--range Weather Forecasts ([14]) 1000 mb winds [15, 16, 17]. From this wind product, we get the analysis quality forcing up to the nowcast time plus a 5-day forecast. The atmospheric forcing for the 30-day forecasts gradually reverts toward climatology after five days.

The thermal fluxes also come from FNMOC NOGAPS, but with the formulation for latent and sensible heat flux replaced by that of [18, 19]. The efficiency of this approach is verified in [19]. The sensible and latent heat fluxes are strongly dependent on SST, and rather than reading them in (i.e., basing them on an external estimate of SST) they are calculated every time step using the model SST. Radiation fluxes also depend to some extent on SST but these are read in because they are strongly dependent on cloudiness that is less readily available. Basing fluxes on model SST automatically provides a physically realistic tendency towards the "correct" SST. If the model SST is too high/low, the flux is reduced/increased relative to that from the correct SST. The trend towards reality is typically not sufficient on its own to keep the model SST on track, but it is sufficient if we also have an "accurate enough" characterization of the temperature just below the mixed layer. In addition to applying the heat flux, the latter temperature is kept on track in NLOM by relaxing the dynamic layer densities back towards climatology (monthly in layer 1, annual otherwise). This approach does not damp anomalies because most of the information about them is the layer thickness variations.

E. The altimeter and SST data

The satellite altimeter data are delivered via NAVOCEANO's Altimeter Data Fusion Center. Both ERS-2 and Topex/Poseidon data are available within 24 hours and the Geosat-Follow-On data within 48 hours. Better orbit corrections are available with a slightly longer delay. This is one reason why the assimilation cycle of the nowcast/forecast system restarts 3 days prior to the nowcast time (next section). As soon as the data from the new satellite altimeters are available, (JASON and ENVISAT), they will be added to the system.

The daily MODAS OI analysis of available MCSST observations is used as data for the SST relaxation in the NLOM system. MODAS is also an operational product running daily at NAVOCEANO.

F. The operational cycle

The nowcast/forecast system was originally running on 216 processors on the Cray T3E at NAVOCEANO Major Shared Resource Center (MSRC). It was transitioned to the IBM SP3 where it is currently running on 132 processors. The transition from the Cray T3E to the IBM SP3 went smoothly due to the scaleable/portable NLOM code [4].

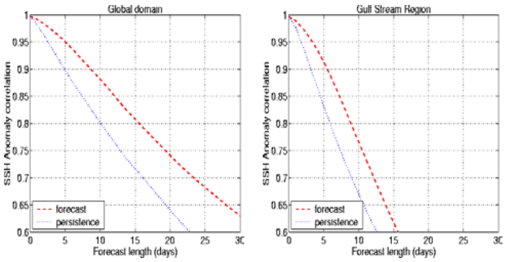
The data assimilation cycle for the system restarts the model three days prior to the nowcast time to pick up newly received data and altimeter data with improved orbits. It uses analysis wind and thermal forcing while SSH and SST data are assimilated up to the nowcast time. This 3-day approach improves the accuracy of nowcasts used to initialize model forecasts. The system performs a daily 4-day forecast, except on Wednesdays when a 30-day forecast is made.

All the scripts controlling the operational run are automated. If all machines and connections are working, the preprocessing scripts will run at a given time of day. If for some reason the nowcast meteorological fields are not available the previous day files will be used and extended with climatology as described above. Post processing of the model output is started as soon as the daily run has finished. The plots and data files are then transferred to local workstations for display on the web page and further calculations of forecast skill and comparisons to available observations are performed, see section III.

III. THE SYSTEM PERFORMANCE AND PRODUCTS

The nowcast/forecast system is routinely compared to independent unassimilated observations for verification. This includes SST and temperature profile data from buoys, tide gauge sea level observations and frontal analyses of MCSST data.

The forecast skill of the model is monitored by comparing the weekly 30-day forecast with the final model analysis. RMS error, anomaly correlation and a climatological skill score are calculated. For the Gulf Stream and Kuroshio the axis error for the current is also computed. Fig. 2a-b shows the average anomaly correlation for 73 30-day forecasts over the period 20 December 2000 and 12 June 2002. Fig 2a shows the results for the global domain while Fig 2b shows the results for the Gulf Stream region. Globally, and in many regions, see the NRL web page http://www.ocean.nrlssc.navy.mil/global_nlom. the model has forecast skill for more than 30 days. (An anomaly correlation higher than 0.6 is used in the literature [20], as a threshold for forecast skill.) In the Gulf Stream region the model does not have forecast skill past 15-17 days. Experiments with a non-assimilative version of NLOM ([21]) showed that a 1/32° version of the model gave a more realistic position, strength and eastward penetration of the Gulf Stream [21].



a b

Fig. 2. Forecast skill of the 1/16° global NLOM showing the anomaly correlation vs time for SSH in a) the global domain and b) the Gulf Stream region.

SST time series from the model are compared to 84 unassimilated observed time series of SST from moored buoys. The statistics from these time series are shown in Fig. 3a-b. Fig. 3a shows the correlation and Fig. 3b the root mean square difference (RMSD) between the time-series. The median correlation is 0.93 and the median RMSD is 0.36°C.

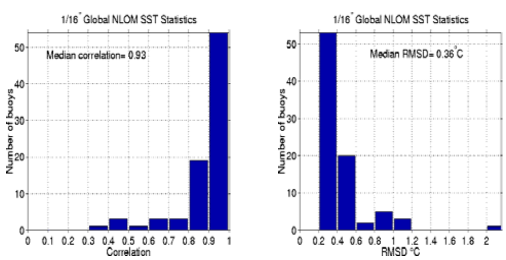


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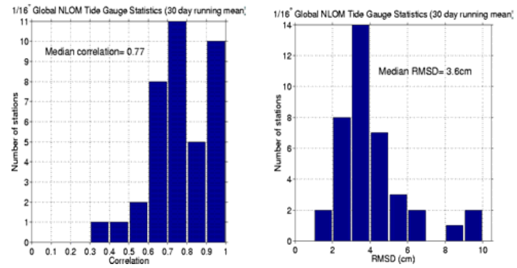
Fig. 3. Statistics between the 1/16° global NLOM SST and 84 unassimilated buoy SST time series, a) correlation between and b) the root mean square difference.

SSH time series from the model are compared to tide gauge time series at 34 stations. The time series have been filtered with a 30-day running mean. These observations are not assimilated into the model. Fig. 4a shows the correlation and Fig. 4b the RMSD between the time-series. The median correlation is 0.77 and the median RMSD is 3.6 cm.

The NRL web page contains results and statistics for 29 different regions of the world oceans. The surface data from the nowcast and the weekly 30-day forecasts are also available in the directory /pub/smedstad/dailyout on the anonymous ftp server ftp7320.nrlssc.navy.mil. A README file in this directory describes how to read the files.



a b

Fig. 4. Statistics between the 1/16° global NLOM SSH and 34 unassimilated tide gauge time series, a) correlation and b) the root mean square difference. The temporal mean over the time period of the observations has been removed.

IV. THE PRESENT AND THE FUTURE

An eddy-resolving global ocean model and prediction system such as this one has a wide range of civilian and military applications. It is a contribution to the Global Ocean Data Assimilation Experiment (GODAE) [22] with the goal to have data-assimilative global ocean models that provide useful real-time global ocean products with wide availability to a broad community of potential users around the world. Applications include assimilation and synthesis of global satellite surface data; ocean forecasting; optimum track ship routing; search and rescue; fisheries and marine resource management; anti-submarine warfare and surveillance; tactical planning; high resolution boundary conditions that are essential for even higher resolution coastal models; input to ice, atmospheric and bio-chemical models and shipboard environmental products; environmental simulation and synthetic environments; ocean research and education; observing system simulation and assessment; impact on ocean structures such as oil rigs; pollution and tracer tracking and inputs to water quality assessment.

As computer power increases, more sophisticated eddy-resolving global models will be available for transition into operational use. Advanced assimilation techniques will also be available, but for eddy-resolving global ocean models it will be a trade off between having high resolution or an advanced assimilation method, e.g. an ensemble Kalman filter. The Hybrid Coordinate Ocean Model (HYCOM) is a candidate for the next generation operational global ocean model. HYCOM is currently being developed under a National Ocean Partnership Program (NOPP) project with E. Chassignet at the University of Miami as the coordinator. It is isopycnal in the open, stratified ocean, but makes a dynamically natural transition to a terrain-following coordinate in shallow coastal areas, and to z-level coordinates in the mixed layer and/or unstratified seas. The hybrid coordinate extends the geographic range of applicability of traditional isopycnic coordinate circulation models such as NLOM, into shallow coastal seas and unstratified parts of the world ocean. The hybrid model maintains the significant advantages of an isopycnal model in stratified regions while allowing more vertical resolution near the surface and in shallow coastal areas, hence providing a better representation of the upper ocean physics. The use of HYCOM will streamline the procedure of driving high-resolution coastal models with output from a basin-scale isopycnic model, since HYCOM will be able to provide the required near-shore data at fixed depth intervals. The hybrid coordinate is obtained via a fully general continuity equation that allows an arbitrary partitioning between density coordinates and depth coordinates on a time step by time step basis (see http://hycom.rsmas.miami.edu and [23] for details).

The goal is to have several different assimilation techniques implemented in HYCOM. This will include simple OI based updating techniques as well as advanced methods including the ensemble Kalman filter. The adjoint code for HYCOM is also being developed. Currently a 1/3° Atlantic version of HYCOM is running in near real time. This model will be upgraded to a 1/12° version in late 2002. An OI based updating scheme, including a vertical projection of the surface data via the Cooper and Haines [25] technique is currently being used in the near real time run. These runs will be used as a baseline to which the results from the more advanced techniques will be compared. A web page showing the results from this prototype system is under development and should be available in late 2002.

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